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# Interuniversity Attraction Poles (IAP)
# Phase VI

## 2007 – 2011

**ANNEX I**

**TO CONTRACT P6/23**

## TECHNICAL SPECIFICATIONS : SECTION I

**Information on the network**

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| Title of the project : Advanced Research on Exotic Nuclei for Nuclear Physics and Nuclear Astrophysics |
| Name of the coordinator : Piet Van Duppen<br><br>Institution : Katholieke Universiteit Leuven |

## I. 1. NETWORK COMPOSITION

BELGIAN PARTNERS *

| | |
|---|---|
| Coordinator : Partner 1 (P1)<br>Name : Piet Van Duppen<br>Institution : Katholieke Universiteit Leuven<br>Institution's abbreviation : K.U.Leuven | Partner 8 (P8)<br>Name :<br>Institution :<br>Institution's abbreviation : |
| Partner 2 (P2)<br>Name : Pierre Descouvemont<br>Institution : Université Libre de Bruxelles<br>Institution's abbreviation : U.L.B. | Partner 9 (P9)<br>Name :<br>Institution :<br>Institution's abbreviation : |
| Partner 3 (P3)<br>Name : Kris Heyde<br>Institution : Universiteit Gent<br>Institution's abbreviation : U.Gent | Partner 10 (P10)<br>Name :<br>Institution :<br>Institution's abbreviation : |
| Partner 4 (P4)<br>Name : Hamid Aït Abderrahim<br>Institution : Studiecentrum voor Kernenergie<br>Institution's abbreviation : SCK•CEN | Partner 11 (P11)<br>Name :<br>Institution :<br>Institution's abbreviation : |
| Partner 5 (P5)<br>Name :<br>Institution :<br>Institution's abbreviation : | Partner 12 (P12)<br>Name :<br>Institution :<br>Institution's abbreviation : |
| Partner 6 (P6)<br>Name :<br>Institution :<br>Institution's abbreviation : | Partner 13 (P13)<br>Name :<br>Institution :<br>Institution's abbreviation : |
| Partner 7 (P7)<br>Name :<br>Institution :<br>Institution's abbreviation : | |

* Mention only **one** name per partner. The person listed here should be the one in charge of the operational aspects of the project. Indicate the full name (family name + first name) of the partner.

EUROPEAN PARTNERS * (if applicable)

| | |
|---|---|
| EU-Partner 1 (EU1)<br>Name : Philippe Chomaz<br>Institution : Grand Accelerateur National d'Ions Lourds, Caen<br>Institution's abbreviation : GANIL<br>Country : France | EU-Partner 3 (EU3)<br>Name : Jan Jolie<br>Institution : Universität zu Köln, Köln<br>Institution's abbreviation : IKP<br>Country : Germany |
| EU-Partner 2 (EU2)<br>Name : Christoph Scheidenberger<br>Institution : Gesellschaft für Schwerionenforschung, Darmstadt<br>Institution's abbreviation : GSI<br>Country : Germany | EU-Partner 4 (EU4)<br>Name : Gabriel Chardin<br>Institution : Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, Orsay<br>Institution's abbreviation : CSNSM<br>Country : France |

* Mention only **one** name per partner. The person listed here should be the one in charge of the operational aspects of the project. Indicate the full name (family name + first name) of the partner.

## I. 2. TITLE AND SUMMARY OF THE PROJECT

Indicate clearly and briefly the project's major objectives and provide a concise description of the project.

### A. Title and summary in English (2 pages maximum)

"Advanced Research on Exotic Nuclei for Nuclear Physics and Nuclear Astrophysics"

The proposed network brings together the Belgian expertise on theoretical and experimental nuclear physics, nuclear astrophysics and accelerator driven systems, and will execute, in a coherent and collaborative effort, a research program focussed around radioactive ion beam research. Together with the EU partners, a carefully selected sample of atomic nuclei most of them with extreme proton to neutron ratios will be studied to bring key elements for a better understanding of the manifestation of the strong, weak and electromagnetic interaction in the nuclear medium.

Key experiments on the properties of exotic nuclei through decay, moment and reactivity measurements are proposed while the beta decay of specific isotopes will serve the weak interaction studies. Theoretical studies are directed towards few-body models, mean field descriptions and shell models and their symmetries. The results will be used for nuclear-structure studies, weak interaction studies and nuclear astrophysics, as well as to investigate fundamental nuclear physics aspects of accelerator driven systems.

Based on the achievements and the expertise acquired from the present IAP network and in line with the international situation we propose a continuation of our research program whereby the importance of nuclear-structure research on and weak interaction studies with exotic nuclei increases substantially, neutron-capture experiments and an applied component related to accelerator driven systems are added.

The network has been extended with the experimental neutron physics group from U.Gent and the MYRHHA SCK•CEN group specialized in accelerator driven systems. New EU partners are the Institute of Nuclear Physics of the University of Köln, UNI Köln (Köln, Germany) and the Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, CSNSM (Orsay, France). These new partners bring novel expertise and re-enforce existing expertise in the network: high-level instrumentation for gamma-ray detection, in-beam spectroscopy, lifetime measurements, neutron physics, high-intensity proton radiation target stations, symmetry based nuclear modelling, mean-field calculations to name a few. The increased emphasis on exotic nuclei research and the embryotic study of some fundamental aspects of ADS has introduced a further reorientation of the program that was already initiated during the present phase.

An extended experimental campaign at the radioactive beam facilities of Louvain-la-Neuve (Belgium), ISOLDE-CERN (Switzerland), GANIL (France) and GSI (Darmstadt) and at the SCK•CEN and GELINA (Belgium) and ILL (France) neutron facilities is planned. Smaller campaigns at other facilities are foreseen as well. The major theoretical efforts will be closely related to the experimental work in order to stimulate mutual feedback between theory and experiment. This results in the research program that covers the following topics:

- Study of light exotic nuclei: structure, decay properties and reactivity: few-nucleon correlation effects, clusters structures, halo and skin structures

- Study of medium-heavy and heavy nuclei with a closed shell configurations for protons or neutrons: effective interactions in nuclei with extreme N/Z ratio, shape coexistence

- Study of nuclei along the N=Z line: pairing correlations, deformation driving phenomena, exotic decay modes, T=1 and T=0 interactions, weak interactions

- Set-up effective interactions that will allow unrestricted shell-model studies for the largest possible model spaces in order to explore better the extremes of the nuclear shell model and an effective interaction, in the form of an energy density functional, in conjunction with a beyond mean-field method.

- Study of the nuclear physics aspects of reactions of astrophysics interest

- Study of rare actinides: nuclear structure, neutron-capture, accelerator driven systems

The proposed network lays down the Belgian research activities in nuclear physics to bridge the gap between now and the commissioning of the two major nuclear-physics facilities FAIR – GSI and EURISOL that are currently under construction/discussion in Europe. These activities will guarantee a continued visible role of Belgian research groups on the international scene of nuclear physics research.

## B. Title and summary in Dutch (2 pages maximum)

“Exotische atoomkernen voor kernfysisch and nucleair astrofysisch onderzoek”

Het voorliggende project bundelt de Belgische expertise op het gebied van de theoretische en experimentele kernfysica, de nucleaire astrofysica en de versneller-gedreven fissie systemen (ADS: Accelerator Driven Systems) en beoogt via een coherente samenwerking een onderzoeksprogramma uit te voeren rond radioactieve ionenbundels. In samenwerking met enkele Europese partners zullen een aantal zorgvuldig uitgekozen kernen, meestal met een extreme neutron tot proton verhouding, bestudeerd worden om vitale informatie te leveren die een beter inzicht zal verschaffen over de sterke, zwakke en elektromagnetische krachtwerking actief in het nucleair medium.

Een reeks experimenten wordt vooropgesteld waarbij de eigenschappen van exotische kernen bestudeerd worden via het radioactief verval, via elektrische en magnetische momentmetingen en kernreacties en waarbij precisiemetingen op het betaverval informatie opleveren over de zwakke interactie. Theoretische studies concentreren zich op weinig-deeltjes modellen, gemiddelde veldbeschrijvingen en schillenmodellen met hun symmetrie. De resultaten zullen niet enkel belangrijk zijn voor zuiver kernfysische structuurproblemen, voor de studie van de zwakke interactie en voor het kernfysisch aspect in astrofysische problemen maar ook voor de kernfysische aspecten in de problematiek van radioactief afvalverwerking via versneller gebaseerde systemen.

Dit project is een voortzetting van het onderzoeksprogramma opgezet in het huidige IAP netwerk en steunt sterk op de verworven ervaring en expertise. Maar toch zijn er belangrijke accentverschuivingen naar een versterking van het kernstructuurprogramma en de studie van de zwakke interactie. Tevens is er een uitbreiding met een programma rond neutron-vangstreacties en met een toegepast luik rond versneller-gebaseerde systemen.

Het netwerk wordt uitgebreid met de experimentele neutronenfysica groep van de Universiteit Gent en met de MYRHHA groep van het SCK-CEN, Mol die gespecialiseerd is in versneller-gebaseerde systemen. De nieuwe EU partners zijn het Institut für Kernphysik van de Universität Köln, Duitsland en het Centre de Spectrometrie Nucleaire et de Spectroscopie de Masse, CSNSM, Orsay, Frankrijk. Deze nieuwe partners versterken niet alleen de expertise binnen het netwerk maar reiken ook nieuwe expertise aan: hoog-kwalitatieve instrumentatie voor ☐ detectie, in-bundel spectroscopie, levensduur metingen, neutronen fysica, trefschijven voor hoog-intense protonenbundels, symmetrie-gebaseerde kernmodellen, gemiddeld-veld berekeningen om er maar enkele te noemen. De accentverschuiving naar meer onderzoek van exotische kernen, reeds gestart in de huidige fase, wordt hiermee doorgezet en uitgebreid met een verkennende studie rond mogelijke kernfysische aspecten van het versnellers-gebaseerd ADS onderzoek.

Uitgebreide experimentele campagnes zullen opgezet worden aan de versnellers van Louvain-la-Neuve ISOLDE-CERN, Geneve, Zwitserland, GANIL, Caen, Frankrijk en GSI, Darmstadt, Duitsland alsmede aan de neutronbronnen van het SCK-CEN, Mol, GELINA, Geel en ILL, Grenoble, Frankrijk. Een aantal kleinere experimenten aan andere opstellingen wordt ook voorzien. De theoretische ontwikkelingen zijn sterk gekoppeld aan het experimenteel werk om zoveel mogelijk stimulansen en terugkoppeling te krijgen tussen theorie en experiment. Daarmee bestaat het onderzoeksprogramma uit de volgende luiken:

- studie van lichte, exotische kernen: structuur-, verval- en reactie-eigenschappen met nadruk op effecten als gevolg van correlaties, clustervorming, halo- en oppervlakte fenomenen
- studie van middelzware en zware kernen met een gesloten schilconfiguraties: effectieve interacties in kernen met een extreme proton tot neutronverhouding, vormcoëxistentie
- studie van kernen rond de N=Z lijn: paringscorrelaties, deformatie-gestuurde fenomenen, exotische vervalwijzen, isospininteracties, zwakke interacties

- opstellen van effectieve interacties voor onbeperkte schillenmodel-berekeningen in de grootst mogelijke configuratieruimte met als doel de grenzen van het schillenmodel af te tasten en van effectieve interacties op basis van energiedichtheidsfuncties voor verkenningen verder reikend dan de gemiddelde veldbenadering
- studie van kernfysische aspecten in kernreacties met astrofysische inslag
- studie van zeldzame actinides: kernstructuur, neutronvangst en versneller-gebaseerde systemen.

Het voorgestelde netwerk legt de Belgische onderzoeksactiviteiten in de kernfysica vast om de kloof te overspannen tussen nu en het in gebruik nemen van twee nieuwe grootschalige kernfysicaprojecten FAIR-GSI en EURISOL die nu onder discussie/ontwerp zijn in Europa. Deze activiteiten zullen er voor zorgen dat Belgische onderzoeksgroepen blijvend een zichtbare rol zullen spelen in de internationale context van het kernfysisch onderzoek.

## C. Title and summary in French (2 pages maximum)

"Recherche avancée sur les noyaux exotiques pour la physique et l'astrophysique nucléaires"

Le réseau proposé rassemble l'expertise belge en matière de physique nucléaire théorique et expérimentale, d'astrophysique nucléaire et de systèmes pilotés par accélérateur; le programme de recherche, mené en collaboration et de manière cohérente, sera centré sur les faisceaux d'ions radioactifs. Un ensemble de noyaux atomiques, présentant pour la plupart des rapports extrêmes entre les nombres de protons et de neutrons, sera étudié avec plusieurs partenaires européens; ces noyaux seront soigneusement sélectionnés pour considérablement améliorer la compréhension des manifestations des interactions forte, faible et électromagnétique dans le milieu nucléaire.

Il sera proposé des expériences clés sur les propriétés des noyaux exotiques au travers de mesures de décroissance, de moment et de réactivité; les études de l'interaction faible se feront quant à elles au moyen de la décroissance beta d'isotopes spécifiques. Par ailleurs, les études théoriques porteront sur des modèles à quelques corps, des descriptions en champ moyen et des modèles en couches, ainsi que sur leurs symétries. Les résultats serviront aux études de la structure nucléaire, de l'interaction faible, de l'astrophysique nucléaire, et seront également appliqués aux systèmes pilotés par accélérateur.

Forts des réalisations et de l'expertise acquises dans le cadre de l'actuel réseau PAI et conformément à la situation internationale, nous suggérons de poursuivre un programme de recherche basé sur deux axes: d'une part, un renforcement considérable de l'étude de la structure nucléaire et des interactions faibles dans le domaine des noyaux exotiques; d'autre part, l'adjonction d'expériences de capture de neutron et l'ajout d'une dimension appliquée à travers des questions de physique nucléaire fondamentale liées aux systèmes pilotés par accélérateur.

Au réseau se sont ajoutés le groupe de physique neutronique expérimentale de l'Université de Gand de même que le groupe MYRHHA du Centre d'étude de l'Énergie Nucléaire (CEN, Mol), spécialisé dans les systèmes pilotés par accélérateur. Nous accueillons également de nouveaux partenaires européens: l'Institut de Physique Nucléaire de l'Université de Cologne (Allemagne) et le Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse (CSNSM, Orsay, France). Leur contribution se traduit tant par l'apport d'une expertise nouvelle que par le renforcement de l'expertise existante au sein du réseau: citons entre autres une instrumentation de haut niveau en matière de détection gamma, de spectroscopie en ligne, de physique du neutron; des cibles à haute irradiation proton; des modèles nucléaires basés sur les symétries ou sur les calculs en champ moyen. La mise en exergue accrue de la recherche sur les noyaux exotiques et l'étude embryonnaire de certains aspects fondamentaux des systèmes pilotés par accélérateur ont en effet amené une réorientation du programme, et ce dès la phase en cours.

Nous prévoyons de mener une vaste campagne expérimentale sur plusieurs sites: Louvain-la-Neuve, ISOLDE-CERN (Genève, Suisse), GANIL (Caen, France) et GSI (Darmstadt, Allemagne) pour les faisceaux radioactifs et CEN, GELINA (Mol) et ILL (Grenoble, France) pour les neutrons. Des campagnes de moindre envergure sont également prévues sur d'autres installations. L'essentiel des développements théoriques sera étroitement lié aux travaux expérimentaux afin d'encourager les échanges entre ces deux pôles. Par conséquent, le programme de recherche couvrira les sujets suivants:

- étude des noyaux exotiques légers: structure, propriétés de décroissance, réactivité; effets de corrélation à quelques nucléons, structures en amas, en halo, en peau de neutrons;

- étude des noyaux semi-lourds et lourds avec une configuration en couche fermée pour les protons ou les neutrons: interactions effectives dans les noyaux de rapport N/Z extrême, coexistence de forme;

- étude des noyaux le long de la ligne N=Z: corrélations d'appariement, origine des déformations, modes de décroissance exotiques, interactions T=1 et T=0, interactions faibles;

- Mise sur pied d'interactions effectives permettant des calcules de modèle nucléaire en couches sans restrictions sur la tailles de l'espace du modèle, dans le but de mieux explorer les limites de ce modèle ; mis sur pied d'une interaction effective, sous la forme d'une fonctionnelle de densité d'énergie, en conjonction avec une méthode au-delà du champ moyen.

- étude des aspects de physique nucléaire liés aux réactions d'intérêt astrophysique;

- étude des actinides rares: structure nucléaire, capture de neutrons, systèmes pilotés par accélérateur.

Enfin, le réseau structurera la recherche belge en physique nucléaire en vue d'assurer la continuité entre le présent et la mise en service des deux principales installations de physique nucléaire actuellement en construction ou en négociation au niveau européen, FAIR-GSI et EURISOL. Ces activités garantiront la visibilité continue sur la scène internationale des groupes de recherche belges en physique nucléaire.

## I. 3. OBJECTIVES, MOTIVATION AND STATE OF THE ART (5 pages maximum)

Describe the project's objectives and research goals.
Define the problems being addressed by positioning them in relation to the current state of knowledge.

### 1. Introduction

Since its inception the study of atomic nuclei has largely been limited to nuclei near the valley of stability. Theories and paradigms have been developed based on data from those nuclei. Now, in the last decade or so, through technological and theoretical advances, the capability has been obtained to produce and study nuclei far from stability. These nuclei possess truly exotic, unforeseen properties that challenge these paradigms, the benchmarks of the current understanding for half a century. This is revolutionizing the knowledge of the many-body atomic nucleus, revealing new nuclear topologies (e.g., halo nuclei), the physics of loosely bound quantal systems, the interplay of bound levels and the continuum, the special properties of nuclei with equal numbers of protons and neutrons, the fragility of magicity or the melting of shell structure, new collective modes. It has been validly stated that this is the most exciting time in nuclear-structure physics since the 1960s. The field of Radioactive Ion Beams is bound to forge real progress in answering the following crucial and long-standing questions in nuclear structure and nuclear astrophysics:

- How were the chemical elements created during the evolution of our universe? How is the energy generated in stars?
- What are the limits for existence of nuclei? Where does Mendeleyev's table end?
- How does the effective nuclear force depend on the varying proton-to-neutron ratios?
- How to explain collective phenomena from individual motion?
- How are complex nuclei built from their basic constituents?
- What are the fundamental properties of the interactions at play in atomic nuclei?

The central questions mentioned above are related to understanding the composite way in which matter appears starting from its major building blocks that go all the way down to nuclei, nucleons and the underlying quark-gluon structure. At the same time, physicists try to unravel the forces that bind these constituents and understand possible symmetries that are present at the higher energy scales. It is important to stress the line of evolution from the early phases in the universe, through star formation with element synthesis into present-day efforts to probe the limits of stability with experimental methods and at the same time deepening our theoretical understanding of those processes. The field of nuclear physics has seen an increasing synergy with other disciplines stressing more the unity than the separation between sub-fields. The new field of energetic Radioactive Ion Beams plays a key role in this research endeavor.

It is therefore worldwide recognized that this new field should be fully developed and exploited in the coming years, a conclusion taken by the nuclear physics communities in Europe, North-America and Japan. In Europe, NuPECC (Nuclear Physics Collaboration Committee, an Expert Committee of the European Science Foundation) published its Long Range Plan 2004: "Perspectives for Nuclear Physics Research in Europe in the Coming Decade and Beyond" as well as a report on "Nuclear Science in Europe: Impact, Applications, Interactions" in 2002. In the 2004 Long Range Plan it is stated that the future of nuclear physics research lies in truly European projects, surpassing the possibilities of individual countries. Scientific priorities together with recommendations have been formulated and road maps to achieve these research goals developed. The 2002 report highlights the importance of development programs related to Accelerator Driven Systems (ADS). In the scope of these research priorities and strategy, focusing on energetic Radioactive ion beams and ADS related fundamental physics research, this IAP network combines the available expertise in Belgium.

2. The network's goal and the international context.

Nuclear physicists have used all possible stable isotopes that Nature provides for projectiles and targets in accelerator experiments. Even long-lived radioactive isotopes have been used as beam or as target. This has led to the synthesis in laboratories of some 2300 nuclides. But modern nuclear theory predicts that more than 6000 nuclides should exist. Part of this "terra incognita" is simply inaccessible with the conventional combination of stable beams and targets. Only radioactive ions, produced in a primary reaction and then kept at or brought to such energies that they can on their turn induce a secondary reaction could reach out in this unknown territory. Furthermore the knowledge of the 2300 nuclides studied today is rather limited and involves mainly decay properties and some information on their excited states. Contemporary theories have a limited predictive power, which is not simply due to a "wrong" set of parameters or an oversimplified approximation. It hints to new basic ingredients that have to be implemented in the interactions used.

In order to explore these missing ingredients, to improve the predictive power of the models used, to get a deeper understanding of the underlying symmetries in Nature and to answer the above-mentioned questions, the properties of the atomic nuclei with varying proton-to-neutron ratio have to be studied. **A combined theoretical and experimental study of the decay properties, energy levels, spin and parities, moments, transition matrix elements and reaction probabilities of a selected sample of exotic nuclei, in order to bring elements to answer the above-mentioned questions, is the main goal of the present network.** The network will pursue this goal by making extensive use of radioactive ion beams, neutron beams and radioactive targets. These tools are not only important for nuclear-structure studies, but also for fundamental interaction studies and nuclear astrophysics as well as for the applied field of waste treatment. Especially reaction data on selected sets of radioactive nuclei are important input for the latter two.

Beams of radioactive ions can be produced in two complementary ways leading also to complementary physics. The so-called ISOL (Isotope Separator On Line) method produces unstable nuclei with a first accelerator, these products are stopped and then led to an ion source. After ionization, the ions are extracted, mass analyzed and eventually accelerated to the desired energy. The IF (In-Flight) method relies on the kinematics of the nuclear reaction producing the unstable nuclei. After their flight out of the target the radioactive ions are purified in electric and magnetic fields and then directed on a target or injected in a storage ring, depending on the experimental requirements. Facilities for radioactive ion beam research exist in North-America (TRIUMF – Canada, HRIBF Oak-Ridge and NSCL Michigan State University, U.S.A.) as well as in Japan (RI Beam Factory RIKEN). US scientists are presently investigating the different options for a new generation facility. In Europe four major radioactive ion beam facilities produce a wide spectrum of beams: Louvain-la-Neuve (Belgium), ISOLDE-CERN (Switzerland), GANIL (France) and GSI (Germany). In NuPECC's long range plan it is stated that on the long term two new major facilities are needed in Europe, one based on the IF method and crystallized in the FAIR project at GSI, Darmstadt, Germany and one based on the ISOL method called the EURISOL project. Because of the long time-line of both FAIR and EURISOL, NuPECC supports projects which have intermediate planning and will be realized on a shorter time-scale. These projects will allow one to bridge the gap between now and the operation of FAIR and EURISOL. **The present proposal lays down the Belgian research activities to bridge this gap.**

3. The research objectives

The proposed scientific program focuses on intertwined theoretical and experimental efforts to study exotic nuclei for nuclear physics, nuclear astrophysics, fundamental interactions as well as applications. Key experiments concern the properties of exotic nuclei through their decay and reactions with stable targets or beams and through the study of their atomic structure, and the use of radioactive decay to study fundamental interactions. Theoretical efforts will concentrate on few-body models, beyond mean-field descriptions, shell models and their symmetries. The network has been

extended with two new Belgian partners, an experimental group from U.Gent and with the ADS-MYRHHA group from SCK•CEN and two new EU partners, the CSNSM – Orsay (France) and the University of Köln (Germany).

Based on the achievements during the previous IAP network phases, the expertise now present in the research groups from all partners and in-line with NuPECC's recommendations, we propose a research program covering the following research topics.

- Study of light exotic nuclei: structure, decay properties and reactivity: few-nucleon correlation effects, clusters structures, halo and skin structures

- Study of medium-heavy and heavy nuclei with a closed shell configurations for protons or neutrons: effective interactions in nuclei with extreme N/Z ratio, shape coexistence

- Study of nuclei along the N=Z line: pairing correlations, deformation driving phenomena, exotic decay modes, T=1 and T=0 interactions, weak interactions

- Set-up effective interactions that will allow unrestricted shell-model studies for the largest possible model spaces in order to explore better the extremes of the nuclear shell model and an effective interaction, in the form of an energy density functional, in conjunction with a beyond mean-field method.

- Study of the nuclear physics aspects of reactions of astrophysics interest

- Study of rare actinides: nuclear structure, neutron-capture, accelerator driven systems

The study of these topics together with the experimental tools (instrumentation) and theoretical tools that need to be developed, result in a number of objectives. These objectives are listed below and will be described in detail in the next section:

*Objective 1:*
*We want to increase the selectivity of the LISOL laser ion source and to optimise the experimental conditions at the Penning trap based WITCH (ISOLDE) and SHIPTRAP (GSI) projects.*

*Objective 2:*
*We want to model and analyse a selected set of nuclear reactions of astrophysics interest, including an experimental study of neutron-capture reactions.*

*Objective 3:*
*We want to investigate the properties of key states in light exotic nuclei, compare them with the theoretical models developed within the collaboration, and understand the possible influence on the reaction mechanism at energies around the Coulomb barrier.*

*Objective 4:*
*We want to study medium-heavy and heavy closed shell nuclei in order to obtain key information to test and improve the predictive power of nuclear models far from stability*

*Objective 5:*
*We want to study the nuclei along the N=Z line elucidating the neutron-proton pairing interaction, verifying isospin symmetry and studying the weak interaction in the atomic nucleus.*

*Objective 6:*
*We want to study neutron-capture reactions on rare isotopes of interest for astrophysical and nuclear waste transmutation processes.*

*Objective 7:*
*We want to investigate the feasibility of using the high power proton beam that will become available in the MYRRHA accelerator driven system for Belgian fundamental nuclear-physics research.*

4. Future outlook beyond the network

The research proposed for this network follows closely the evolution of fundamental research worldwide. It's experimental and theoretical program is strongly embedded in the four major facilities for radioactive ion beam research in Europe. At the same time the proposed network's activities prepare Belgian research to embark in the major facilities that are currently under construction (FAIR – GSI) or study (EURISOL). Naturally, the group has more experience in the ISOL technique and main emphasis lies in this direction but discussions on joining experimental programs at FAIR are ongoing. By the very active participation in ISOLDE and GANIL, including HIE-ISOLDE and SPIRAL-2, the network will bridge the time gap mentioned above. It should be noted that several groups from the partners are actively involved in preparing these facilities.

These network activities will allow the Belgian nuclear physics groups to obtain unique data and to perform unique theoretical studies for a better understanding of the nuclear structure and the fundamental interactions at play in the atomic nucleus. It will allow Belgian groups to play a visible role at and around the future facilities and to train highly qualified young scientists in fundamental and applied physics, and in astrophysics.

## I. 4. DETAILED DESCRIPTION OF THE PROJECT (15 pages minimum, 25 pages maximum)

- Submit a general description of the project as well as a description detailing each workpackage and indicate the partners involved in each workpackage.
- Illustrate by means of a table or scheme the interaction between the partners within a workpackage and the interaction between the workpackages.
- Describe and justify the methods and proposed approaches in relation to the state of the art.
- Describe and justify how the contribution of the different partners will be integrated.

1. Introduction

The proposed network brings together and builds on the expertise in nuclear physics research in Belgium. The general, long-term goal of the proposed network is to study the manifestation of the strong, weak and electromagnetic interaction through combined theoretical and experimental studies on exotic nuclei. The study of the decay properties, energy levels, spin and parities, moments, transition matrix elements and reaction probabilities on a selected sample of exotic nuclei is proposed. Apart from this scientific objective, the network aims to prepare Belgian nuclear physicists to take up a visible role in the radioactive ion beam research at the new RIB facilities that are currently proposed/under construction in Europe (FAIR and EURISOL) and that will be operational around 2015.

2. Research objectives and work packages

The above-mentioned goals lead naturally to a number of work packages that are described below. Most of the work presented in this proposal is executed in a large international collaboration but for clarity we only mention the partners from the present network in conjunction with a certain work package.

*2.1 Preparation of radioactive ion beams*

**- The LISOL laser ion source**

At the Leuven Isotope Separator On-Line (LISOL) facility, coupled to the Louvain-la-Neuve cyclotron, the K.U.Leuven developed a laser ion source based on resonance ionisation of short-lived exotic nuclei stopped in a gas cell. Light- and heavy- ion fusion evaporation reactions as well as proton induced fission reactions are used for the production of the radioactive isotopes. A vigorous development program to improve the performances (efficiency and selectivity) of the laser ion source is ongoing, but at the same time the decay properties of these produced exotic nuclei are, after mass separation, studied. Interesting results have been obtained recently on the study of nuclei along the N=Z line and of neutron-rich fission products around the Z=28 closed shell (see objectives 4 and 5). The current limitation for these studies often stems from the limited selectivity of the produced radioactive ion beams.
The laser ion source group is, as activity coordinator, involved in a Joint Research Activity under EURONS (EU-FP6). The latter JRA aims at the development of tools and performance of R&D for the resonance ionisation laser ion source in order to produce pure ground-state and isomer beams of exotic nuclei and develop the in-source laser spectroscopy of short-lived nuclei and to accumulate, cool, bunch and polarize radioactive ion beams.
In order to extend the range of nuclei further out of stability, we plan, within the proposed network, to increase the selectivity of the ion source. The intense research program and strong investment in gas purifying issues, a key element in the performance of any gas catcher system, has resulted in a much better control of the purity of the gas and in an increased efficiency of the laser ion source. Unfortunately, as the unwanted ions survive for a longer time, a decrease of selectivity results. Different ways to increase the selectivity have been investigated. Where electrical fields were an

obvious choice to remove the unwanted ions and electrons, it turned out that they can only be applied effectively if the ionisation rate is far below the typical rate at play in our laser ion source. Controlled addition of impurities was another research project, which resulted in a better understanding of the physico-chemical processes in the gas cell, but due to the very delicate balance between the added of impurities (amount and type) and the number of impurities released by the heated target entrance and exit windows it was not possible to obtain controllable conditions with increased selectivity. A way out that will be investigated in detail within the network is a physical separation of the production gas chamber from the ionisation gas chamber. First preliminary tests using an off-line gas cell with two physically separated chambers have been performed using a Cf fission source and show that the loss factor for the efficiency is only 50%. On-line tests will allow a quantitative measure of the improved selectivity and will also be used to optimise the gas cell geometry. The inclusion of electrical fields in the low space-charge region (in the ionisation region) will remove the photo-electrons improving the efficiency and also decrease the evacuation time. Both proton-induced fission (for neutron-rich nuclei along the Z=28 line) and heavy-ion fusion evaporation reactions (for neutron deficient nuclei along the N=Z line) will be used.
New laser ionisation schemes using the LISOL excimer pumped dye laser system for elements like Cr, V and other elements will be investigated in order to allow decay studies of these nuclei as well.

**- The WITCH and SHIPTRAP projects**
SHIPTRAP at GSI is a set-up for precision experiments on short-lived nuclei produced by fusion evaporation reactions and separated by the velocity filter SHIP. SHIPTRAP is situated behind the SHIP velocity filter and consists of three functional parts:
(a) a buffer gas-filled stopping cell to stop and thermalize the separated reaction products,
(b) extraction and cooler RFQ structures to extract, cool and bunch the ions within a few milliseconds, and
(c) the double trap-system consisting of two cylindrical Penning traps, where the first trap is used for isobaric purification and the second trap is optimized for precision mass measurements by the time-of-flight ion cyclotron resonance technique. Both traps are installed in a room-temperature bore of a superconducting 7-Tesla magnet.
SHIPTRAP has been commissioned in the last few years and was characterized in on-line and off-line experiments in some detail. The sensitivity is demonstrated by the mass measurement of the ground-state proton emitter $^{147}$Tm, which is produced with a cross section as low as 200 μb. In 2005 and early 2006 several production runs were carried out with $^{50}$Cr and $^{58}$Ni beams on nickel targets reaching the area of neutron-deficient Sn isotopes. With SHIPTRAP, there exists a powerful instrument to perform precision measurements on neutron-deficient isotopes of all elements, in particular refractory elements. However, to explore the new experimental opportunities in this area and to apply trap-assisted spectroscopy it is necessary to increase the efficiency and also selectivity of the stopping process.
We propose to bring in the important experience gained at the LISOL gas cell and work in a collaborative effort towards most exotic nuclei along the N=Z line at SHIPTRAP. In detail we plan to:
(a) investigate and improve the SHIPTRAP gas cell,
(b) to determine the stopping distribution of the fusion-evaporation residues in the gas cell using advanced nuclear spectroscopy techniques to optimize the stopping process and gain in overall efficiency and
(c) to use the improved conditions and proceed towards trap assisted decay spectroscopy along the N=Z line.
The described efforts will go along with activities outside of the planned network that target the same object, an improved performance of the complete SHIPTRAP system and its components (in-flight separator, stopping cell, trap system). This will be pursued in a combination of detailed simulations based on the Monte-Carlo code MOCADI, cross sections and excitation-function measurements and transmission studies for different ion-optical settings of SHIP. A key point for the success of this endeavor will be the close collaboration to exchange know how on gas catcher systems and their coupling to in-flight separators. After these optimisation, mass measurements and complementary beta-decay studies along the N=Z line are planned (cfr. work package 5.)

The WITCH project has been set-up by the K.U.Leuven at ISOLDE and combines a double-Penning trap with an electrostatic retardation spectrometer (see also work package 5). In view of future applications of the WITCH system that do not include the retardation spectrometer but will instead make use of the system for the strong (up to $10^6$-$10^7$ decays/s) and the isotopically pure sources it can prepare, a feasibility and design study will be made for combining WITCH with several spectroscopy-type detection set-ups (e.g. SiLi detector(s), Si PIN diodes, tape station, … ) to perform e.g. half-life measurements, observe X-rays and low energy gamma-rays, conversion electrons, etc. The WITCH group is, as activity coordinator, involved in a Joint Research Activity under EURONS (EU-FP6). The goals of this JRA are to perform in-trap spectroscopic studies of rare isotopes, improve the capabilities, precision and sensitivity of existing trap set-ups, and perform precise recoil ion spectroscopy. This is realized by developing multi-purpose set-ups for precision decay spectroscopy experiments in ion traps, developing new trap configurations to house large solid angle detection set-ups, enhancing the performance of experiments by using dedicated new electron- and ion sources and developing retardation spectrometers for high-resolution recoil-ion spectroscopy and for trap-assisted spectroscopy measurements.

**Objective 1:**
**We want to increase the selectivity of the LISOL laser ion source and to optimise the experimental conditions at the Penning trap based WITCH (ISOLDE) and SHIPTRAP (GSI) projects.**

| | **Workpackage 1:**<br>**Preparation of radioactive ion beams** | **Partners** |
|---|---|---|
| 1 | Optimisation of the LISOL laser ion source and development of new laser ionisation schemes | K.U.Leuven |
| 2 | Optimisation of the overall experimental conditions at SHIPTRAP related to studies along the N=Z line | K.U.Leuven – GSI |
| 3. | Feasibility study to perform spectroscopy measurements with WICH and SHIPTRAP | K.U.Leuven – GSI |

*2.2 Study of reactions of astrophysical interest*

This objective deals with theoretical work to calculate and/or analyse relevant reaction data combined with experimental efforts on neutron-capture cross sections.

*Microscopic models*
Theoretical studies on nuclear astrophysics will be developed in several directions. Microscopic cluster models are applied by the U.L.B. group since many years. They provide a fairly strong predictive power, since they essentially depend on an effective nucleon-nucleon interaction, and on some assumptions on the cluster structure of the system. They are efficient in predicting low-energy cross sections for low level-density systems. Further developments will consist in the improvement of the cluster wave functions and of the nucleon-nucleon interaction. Several important reactions, such as $^{12}C(\alpha,\gamma)^{16}O$ or $^{14}N(\alpha,\gamma)^{18}F$ will be considered.
A possible long-term extension of capture models is provided by “ab initio” models, where no assumption is done about a cluster structure, and where realistic nucleon-nucleon interactions are used. For the nuclear spectroscopy studies, different variants are under development in several laboratories: no-core shell model (NCSM) or fermionic molecular dynamics (FMD). Their application to nucleus-nucleus reactions remains a challenge and will be investigated within the present proposal.

*Indirect methods*

Indirect methods play an important role in charged-particle or neutron radiative capture reactions by exotic nuclei when direct measurements are not possible. One approach is the use of breakup reactions to investigate capture reactions involving radioactive nuclei. A good understanding of the relationship between the breakup data, and the relevant cross sections for astrophysics is crucial. Theoretical studies in this direction will be performed. The validity of the Coulomb breakup method will be analyzed with the resolution of the time-dependent Schrödinger equation and with the new dynamical eikonal approximation.
A second approach is the Asymptotic Normalization Constant (ANC) method, which can be applied to capture reactions involving a weakly bound final state (as in $^{7}Be(p,\gamma)^{8}B$ for example). In those conditions the cross sections are essentially given by the properties of the wave functions at large distances. The main input is the normalization amplitude of the bound state. The validity of the ANC method will be tested with the help of the microscopic cluster model.

*Neutron induced reactions*
Neutron induced reactions play an important role in several astrophysical scenarios, from Big Bang nucleosynthesis to explosive nucleosynthesis in supernovae. In collaboration with the experimental and theoretical groups from U.Gent and U.L.B., neutron induced reactions will be studied in a microscopic approach. Resonant as well as non-resonant reaction probabilities will be investigated.
When neutron capture is not dominated by resonances, the non-resonant capture rate needs to be evaluated. Taylor expansions near zero energy of the product of the capture cross section and the relative velocity allow to accurately parameterise the low-energy behaviour. The parameters can be deduced from experiment like in the neutron radiative capture by $^{12}C$ or $^{14}C$, or they can be estimated from the knowledge of energies of bound states and resonances, and of spectroscopic factors. The U.L.B. group plans to search for important cases of this type and provide estimates of their non-resonant cross sections. Spectroscopic factors of some of the nuclei will be determined by the U.Gent group in the framework of shell model calculations.
On the experimental side, the U.Gent group has constructed a dedicated experimental set-up for this type of measurements at a thermal neutron beam of the High Flux Reactor of the Institut Laue – Langevin (ILL) in Grenoble and at the GELINA neutron facility of the Institute for Reference Materials and Measurements (IRMM) in Geel, where resonance and high energy neutrons are available. Both institutes are leading neutron facilities. We will also investigate if complementary studies at the nTOF facility at CERN are needed. In the past, experimental efforts were mainly concentrated on the dominant (n,γ) reactions, although in specific cases the (n,p) or (n,α) channel prevails. The α-particles or protons are detected with suited silicon surface barrier detectors or with a Frisch-gridded gas-flow ionisation chamber, which can be optimised for each specific case. In the coming years, (n,p) and (n,α) reactions on 26Al (T1/2 = 7.16 x 105 y) and 41Ca (T1/2 = 1.03 x 105 y) are planned. The cross section of the reactions mentioned above will be determined as a function of the neutron energy and hence transformed in reaction rates as a function of stellar temperature.

*Reaction data analysis*
The phenomenological R-matrix method is another topic of interest. In astrophysics, the relevant energies are in general much lower than the Coulomb barrier, which makes the cross sections too small to be measured in laboratories. The R-matrix method is very efficient in fitting available experimental data, and in extrapolating them down to stellar energies. Valuable results have been obtained recently in e.g. $^{12}C(\alpha,\gamma)^{16}O$ or $^{14}N(p,\gamma)^{15}O$. In the next phase other reactions will be considered using the tools developed in recent years.

**Objective 2:**
**We want to model and analyse a selected set of nuclear reactions of astrophysics interest, including an experimental study of neutron-capture reactions.**

| | **Workpackage 2:**<br>**Study of reactions of astrophysics interest** | **Partners** |
|---|---|---|
| 1 | Theoretical study of nuclear reactions of astrophysical | U.L.B. |

| | | |
|---|---|---|
| | interest: microscopic models, direct reactions and R-matrix analysis | |
| 2 | Theoretical and experimental study of neutron capture reactions of astrophysical interest | U.Gent – U.L.B. |

<u>*2.3 Light exotic nuclei*</u>

Light nuclei show various peculiar characteristics. Due to the importance of pairing and correlation effects, the few nucleons forming these systems are often grouped in clusters; halos and skin structures may develop in nuclei with an extreme *N*/*Z* ratio; in many systems, the low thresholds for particle breakup influence both the structure and the reaction mechanism. These features represent a challenge for theoretical models: beside mean field approaches, which are questioned by the small number of nucleons of these systems, other models have been developed and can be tested in this region: microscopic and macroscopic few-body models, ab-initio calculations. In this respect, it is of great importance, and a true advantage, that both the experimental <u>and</u> theoretical work is carried out within the proposed network.

**- Experimental studies**

The experimental study of these systems can benefit from the use of radioactive ion beams. At the Cyclotron Research Centre (CRC) in Louvain-la-Neuve and Spiral at GANIL, the ISOL technique is adopted to obtain intense post-accelerated beams of pure isotopic composition, providing the best conditions for measurements. In-flight separation facilities are complementary, for those ion beams that cannot be produced with the ISOL method.

The experimental research is along two lines.

*The study of the structure of light exotic nuclei*

We want to collect crucial experimental information, that can be used to benchmark the different models: in particular, we are interested in the position, width and structure (spin, parity) of bound and unbound states. Several cases are of interest:

- the disputed observation of excited states in $^{7}$He;
- the nature of the ground state of $^{8}$He;
- the halo ground states of $^{11}$Li and $^{14}$Be, and their unbound subsystems $^{10}$Li and $^{13}$Be;
- rotational bands built on molecular states in neutron-rich Be isotopes;
- the study of position and structure of resonances of interest for astrophysical reactions.

These experimental investigations can be carried out using nuclear-reaction techniques and decay studies:

- In nuclear reactions, beams of radioactive nuclei are employed to populate the states of interest via single or multi-nucleon transfers. The cross section of the reaction and the angular distribution of the emitted particles provide the required information. At the CRC in Louvain-la-Neuve we already successfully applied this technique in numerous cases. We want to continue employing the high-quality beams available there, in particular the $^{6}$He beam and Be beams, in transfer reactions such as (p,$\alpha$), (d,p), ($^{9}$Be,$^{8}$Be) and others.
- In decay studies, properties of the mother and daughter states are deduced from the patterns and branching of the beta decay. The advantage of this technique is that the experimental probe (the beta-decay) is a well-known process. In several cases in light weakly bound nuclei, much of the decay strength is concentrated towards states in the continuum of the daughter nucleus: these branches are thus characterized by the coincident emission of light ions. We have refined a method, where the post-accelerated unstable nucleus is implanted in a silicon detector, and the energies of the emitted ions are fully measured. We applied it in several cases already, in particular the deuteron branching of the beta decay of the two-neutron halo nuclei $^{6}$He (at the CRC) and $^{11}$Li (in TRIUMF, Vancouver), and the structure of the Hoyle state in $^{12}$C (KVI, Groningen). Other possibilities are opened by the use of the radioactive beams at these facilities and at Spiral. For example, the structure of the $^{8}$He ground state; the decay of $^{16}$N into states in $^{16}$O close to the $^{12}$C+alpha threshold

(of interest for nuclear astrophysics). In parallel, theoretical studies will be pursued as an application of three-body models (see below). A first example was the 6He nucleus where the weak decay branch 6He-> $\alpha$+d+$\beta$-+n was shown to be an efficient tool to investigate the halo structure of 6He. Further work is in progress on 11Li and will be continued in the future. Other halo nuclei, such as 14Be, might also be studied.

*The effect of the properties of light weakly bound nuclei on the reaction mechanism*

The properties of light weakly bound nuclei are of particular interest in reactions at energies close to the Coulomb barrier. The strong coupling to the direct channels (break-up, transfer) appearing at these energies modifies the interaction potential between projectile and target, with effects on the elastic scattering cross section and possibly on the fusion cross section. The weak binding of the light projectile is at the origin of such effects, through the importance of the break-up channel and the coupling to continuum resonances close to the threshold. Reaction models are being developed for the description of the reaction mechanism, but they still suffer from the poor knowledge of quantities like the parameters of the potentials for the entrance and exit channels, the importance of relative direct channels, and the structure of states involved in the couplings.

Experimental investigation can provide this information in particular with:

- Measurement of the elastic scattering of light weakly bound nuclei on different targets in a wide range of energies, in order to derive reliable parameters of the interaction potential. Of particular interest is the behaviour of the very weakly bound $^{11}$Li halo nucleus.
- Systematic measurements of direct-reaction cross sections, to establish the relative importance of breakup, transfer and inelastic excitation processes.
- Measurement of fusion excitation functions, covering the energy range around the potential barrier. Precise measurements are necessary in order to settle the long-standing debate about the effect of breakup on the fusion mechanism.

The measurement of the fusion cross section of $^{6}$He on U and Zn target at the CRC is among the results already obtained. The program continues with the measurement of elastic scattering (on U and Pb targets) and direct reactions cross sections. The availability of ISOL beams at Spiral allows the measurements of fusion and direct reaction cross sections for $^{6}$He and $^{8}$He on Cu and U targets. The $^{11}$Li beams in development at TRIUMF and REX-ISOLDE will allow the measurement of elastic scattering cross sections.

This spectrum of experimental activities are discussed with and supported by the theory group from U.L.B. (see below).

**- Theoretical studies**

*Cluster models*

Cluster models are well suited to the description of light exotic nuclei, which are made of a core, and of external neutrons (typically one or two). In addition, their low level density is well adapted to a microscopic approach. Typical examples are 6He or 14Be, described as $\alpha$+n+n or 12Be+n+n cluster structures, respectively.

Three-body models are developed in various directions: microscopic and non-microscopic theories are developed, as well as applications to bound and continuum states. In all cases the hyperspherical formalism turns out to be very appropriate. Some work has been done until now on bound states. The new project essentially focuses on continuum states, and on the influence of core excitations in halo nuclei. The microscopic approach is adapted to both directions, but raises essentially two problems. For continuum states, the long range of the cluster-cluster interaction in the hyperspherical formalism needs a very special treatment. In two-body continuum states, the matching of the wave function to the correct asymptotic part can be done exactly. The same formalism has been applied more recently to a non microscopic description of three-body continuum states. It should be adapted to the microscopic approach as well.

On the other hand, these models require huge computer times, especially when the core is not an s-shell nucleus. Preliminary tests have been performed by using the “Grid Computing” developed at a

European level. This impressive computer facility will probably make new developments in the microscopic study of three-body systems possible.

*Break-up models*
One of the main techniques of study of short-lived exotic nuclei is dissociation experiments on light targets by the nuclear force and on heavy targets by the Coulomb force. Such experiments are performed at GANIL, GSI, RIKEN, MSU. The analysis requires elaborate models for reactions, such as the semi-classical method of resolution of the time-dependent Schrödinger equation (TDSE) or the quantal Continuum-Discretized Coupled-Channel method (CDCC).
Recently, a new quantal method known as the dynamical eikonal approximation, based on the TDSE code, has been introduced. The projectile is described by a simple potential model involving a core and a halo nucleon. At sufficiently high energies, this model reproduces experimental data on elastic scattering as well as on break-up in a simpler way than CDCC. It has been applied to the halo nuclei 11Be and 14C. We plan to apply this method to the analysis of other break-up experiments of exotic nuclei such as 8B, 19C or 23O. To this end, we plan to extend this method to take core excitation into account in a coupled-channel description, and to replace the two-body description of the projectile by a microscopic cluster model. In order to be able to accurately compare the results with GSI experiments, relativistic corrections will be introduced. Comparisons will be performed with the CDCC model.
A more distant goal is to apply the semi-classical and dynamical eikonal approximations to the dissociation of two-neutron halo nuclei such as 6He or 11Li for which data exist. This extension requires a three-body model for the projectile so that computer times will drastically increase. In a first step, we plan to analyze these reactions with the much simpler traditional eikonal approximation. This will provide us with a sound basis for extending the TDSE code and then the dynamical eikonal approximation.

**Objective 3:**
**We want to investigate the properties of key states in light exotic nuclei, compare them with the theoretical models developed within the collaboration, and understand the possible influence on the reaction mechanism at energies around the Coulomb barrier.**

| | **Workpackage 3:<br>Light exotic nuclei** | **Partners** |
|---|---|---|
| 1 | Experimental investigation of the structure of light nuclei | K.U.Leuven – U.L.B. - GANIL |
| 2 | Reaction studies around the Coulomb barrier | K.U.Leuven - GANIL |
| 3 | Development and exploitation of cluster models and experimental investigation of light exotic nuclei using beta decay and reaction studies | U.L.B. – K.U.Leuven |
| 4 | Development and exploitation of break-up models for intermediate and relativistic energy reactions with light exotic nuclei | U.L.B. – GSI |

*2.4 Studies of medium-heavy and heavy closed shell nuclei*

The properties of nuclei near closed shells form corner stones for guiding nuclear models to describe and predict the nuclear properties far from stability. Most of these nuclei are unstable and have to be studied through radioactive beam research. Different experimental and theoretical tools have been developed within the present network. In the next phase these tools will be further developed and refined, and used to gather reliable and critical data that extend our understanding of the nuclear structure near and at closed shells far from stability.

The study of neutron-rich nuclei has opened new vistas on nuclear structure. There are now first evidences that magic numbers valid close to the line of stability are lost for nuclei with an exotic ratio

between the number of neutrons and protons. There are still major difficulties to describe these nuclei by either mean-field models and their extensions or by the shell model. The isospin dependence of effective nuclear interactions, which have the form of an energy density functional, does not seem adequate and is, up to now, corrected in a phenomenological way. A consensus seems to emerge that introducing a tensor term in the nuclear interaction could have the desired effect on single particle levels and improve largely the description of nuclei far from stability. This term should be included in the near future in the Skyrme effective interactions and in the different codes that are developed in collaboration between the U.L.B. team and several other groups in France and in the US. The problem of its adjustment is still open and extensive studies of long series of isotopes corresponding to magic numbers along the stability line should be undertaken. In particular, the Ni isotopes will provide a test on isotopes which are mainly spherical. A more difficult case will be the nuclei around the neutron deficient Pb isotopes, for which a first, qualitative, agreement has already been obtained on the description of shape coexistence. On the other hand, we try to carry out large-scale shell-model studies for nuclei as heavy as possible. In order to account for pair excitations across closed shells, it is important to truncate the model spaces still keeping the essential physics elements. Symmetries are a particularly powerful method to approach this problem and in Gent, extensive studies, making use of the symmetries of the Interacting Boson Model (IBM) have been performed for the Pb region. We intend as well to construct effective interactions that allow unrestricted shell-model studies for the largest possible model spaces in order to explore better the extremes of the nuclear shell model in the Pb region. Within the present network and using the available techniques on mean-field approaches and symmetry-truncated shell-model, we should be in a position to try to find the optimal combination between the two approaches to nuclear structure and hope to make important advances in the next period of 4-6 years. However, it is clear that a more detailed understanding of these nuclei will require a much better description of the evolution of shape mixing as a function of neutron number, which depends critically on the isospin dependence of single-particle levels.

**- The neutron-rich region around N=20 and 28: delineation of the “island of inversion”**

At the LISE fragment separator at GANIL, several techniques to study magnetic and quadrupole moments of exotic ground states and microsecond isomeric states have been implemented and developed during the previous IAP phase. A dedicated experimental set-up to perform highly efficient and precise $\beta$-NMR measurements was built. Also, the formalism and set-up to measure quadrupole moments of isomeric states in nuclei not accessible via other methods (mainly neutron-rich) was developed and applied successfully. Finally, a method to measure and optimise the spin-polarization in the selected fragment beams was developed, now allowing now studies on very rarely produced isotopes (down to 1000/s). These developments have been performed in a collaboration between Leuven, CSNSM and GANIL.

In the next phase, all these techniques will be used for investigating details about the changing nuclear structure in medium-heavy nuclei that have a ‘magic’ proton or neutron number. The systematic investigation of g-factors and quadrupole moments in the region around $^{32}$Mg (island of inversion around magic N=20) has already revealed important information about the transition from the ‘normal’ sd-shell region into the island of nuclei with an intruder ground state. We will finalize these studies in the near future. A similar onset of deformation was observed in the neutron-rich nuclei along the N=28 magic number, when going from doubly-magic $^{48}$Ca downwards. Furthermore, a drastic change in the proton sd single particle levels is observed when going from N=20 towards N=28. By measuring the g-factors of ground states in the Cl and S isotopes towards (and beyond) N=28, we will pin down the ground state structure and reveal information about this migration of proton levels. These studies will also provide information on the possible breakdown of the N=28 gap with decreasing proton number.

**- The Z=28 Ni region: The influence of exotic neutron-to-proton ratios on the shell structure and the onset of collectivity in the neutron-rich Z=28 region.**

The region of the Ni (Z=28) isotopes spans a large enough interval so as to be able to study changes in the underlying nuclear mean field. Recent experiments carried out by the group at

K.U.Leuven have given access to nuclear structure data that show gradual changes in the single-particle energies. Using shell-model techniques and modern realistic effective interactions, monopole variations have been studied in the odd-mass Cu nuclei. Using simple schematic forces, one notices that two-body tensor forces might be at the origin of specific variations in the single-particle energies. The theory group at U.Gent aims at carrying out a detailed study of both the tensor and two-body spin orbit contributions to variations in the single-particle energies. Getting a better understanding of the relative strength of these force components, relative to the central part, remains a problem to be resolved. One line of attack can come from a decomposition of the realistic forces used now in terms of central, tensor and spin-orbit components while another approach should come from a study of the nuclear mean field including correlations beyond Hartree-Fock theory with the use of energy functionals that also contain tensor force components. In order to reach this goal, more experimental data for the 78Ni nucleus and its surrounding odd-mass nuclei is highly needed (level schemes, transition matrix elements, moments).

*Decay studies of neutron-rich isotopes with Z<28*
A first study is related to decay spectroscopy of neutron-rich iron isotopes populating levels in the Z=27 cobalt isotopes. With the development of the LISOL laser ion source (see objective 1) and the construction of an efficient beta-gamma detection set-up consisting of segmented MINIBALL type germanium detectors, beta decay studies of n-rich iron up to mass 69 isotopes are planned. These decay data provide information on the structure of amongst others the Co isotopes in the neighbourhood of 68Ni. These data will form the completion of the detailed studies that were performed by K.U.Leuven on the decay of n-rich Ni, Cu and Co isotopes. Further studies of neutron-rich Mn, Cr and V nuclei, for which the laser ionisation schemes have to be developed are planned (K.U.Leuven). Combining these data with shell-model calculations from the Gent theory group will allow improvement of an interaction for this region of the nuclear chart. From the instrumentation side, the upgrade of the detection station is planned. Segmented beta detectors and on the $\gamma$-side the use of the 12-fold segmentation (so far only 6-fold segmentation is implemented) including pulse shape analysis will be achieved. This will be accomplished in collaboration with Köln university.

*Moment measurements of n-deficient and n-rich Fe, Ni and Cu isotopes, and heavier masses.*
In the neutron rich region along the Z=28 magic number (Fe, Ni, Cu), several isomeric states have been observed. The g-factors and quadrupole moments of these states can provide information about the quick onset of deformation above and below Ni, as well as on the migration of the proton fp levels with increasing neutron number. The microsecond isomers will be investigated at GANIL, while the longer-lived isomeric and ground state moments will be investigated using the collinear laser spectroscopy at ISOLDE. To investigate even heavier neutron-rich nuclei, more energetic primary beams are needed, such as provided by the GSI accelerators. At the FRS fragment separator, a campaign to measure g-factors of isomers around $^{132}$Sn and in the Pb-region has just finished within the RISING project. These data are now being analysed at several partner institutes. A major goal is to proof the presence of spin-alignment in the relativistic fission of a $^{238}$U beam, which is a requirement for nuclear moments studies. Once this is established and understood, a continuation experiment is considered in the future. In these projects the partners from K.U.Leuven, GANIL, GSI, Köln and CSNSM are involved.

*Coulomb excitation and transfer reaction studies around 68Ni at ISOLDE and MINIBALL*
Within an international collaboration, Coulomb excitation studies and transfer reaction studies are proposed. The ISOLDE facility offers unique possibilities in post-accelerated radioactive ion beams of ground state and isomers. The Coulomb excitation of neutron rich Cu isotopes, whereby post-accelerated isomeric beams are used, has been demonstrated to be feasible and the analysis of the data is ongoing. These experiments were carried out by a large international collaboration with the tandem K.U.Leuven-CSNSM-Orsay as the leading groups. These data reveal transition matrix elements between the different members of the same multiplets thereby forming critical data for testing the above mentioned shell model calculations. This line of research will be continued in the new phase, with different beams of Cu as well as of Ni isotopes (collaboration with Köln). For the

latter, beam developments have to be undertaken. An international collaboration with universities from Belgium, Germany and the U.K. will perform transfer reaction measurements with the post-accelerated ISOLDE beams. A new transfer reaction chamber (based on highly segmented silicon detectors) and new electronics will be constructed. The chamber will be surrounded by the MINIBALL germanium $\gamma$-array. First experiments include one-neutron transfer on Zn, Cu and Ni isotopes to determine the spectroscopic factor and gather information on the wave function of the effective single particle. These data will be compared to large scale shell-model calculations (U.Gent) as well as beyond mean field calculations (U.L.B.). Also two-neutron transfer (using a radioactive 10Be target) will be investigated. The latter experiments will result in information concerning pairing correlations around the N=40 sub-shell closure. Although first experiments will use the 3.1 MeV/u energy of the present ISOLDE set-up, the HIE-ISOLDE energy upgrade (going to 5 and later to 10 MeV/u) will allow a much broader scope of these studies (see further the Pb region).

***- The Z=82 Pb region: Intruder states in the Pb region and the microscopic origin of collectivity***

Closed shell configurations give rise to very peculiar phenomena that put stringent tests on theory. Shape coexistence, whereby the nucleus exhibits two or more different shapes at low-energy, has been observed in the very neutron deficient region around the Z=82 closed shell through alpha-decay studies. The occurrence of a spin triplet of 0+ states has been observed in 186Pb and represents an illustrative example of how apparently the reorganization of only a few nucleons has a strong influence on the collective behaviour and the shape of a nucleus. The very long series of even-even and odd-mass nuclei in the Pb region, starting from the region of nuclei near stability and moving towards the very neutron deficient mass region near and even beyond the N=104 mid-shell region allow to confront the experimental data with results from different nuclear model calculations. For example, the interplay between shell-model degrees of freedom and collective models can be studied in great detail. Apart from a continuation of the successful campaigns at the SHIP velocity filter (GSI) on the alpha decay of extreme neutron deficient isotopes around Z=82, the following experimental programs are planned.

*In source laser spectroscopy of n-deficient Po isotopes*

The evolution of the shape coexisting states when going away from neutron-mid shell at N=104 and the specific coupling of odd neutrons and odd protons to these different shapes are investigated by in-source laser spectroscopic studies at ISOLDE (K.U.Leuven). These studies were successfully conducted for the Pb nuclei and proved that all Pb nuclei remain spherical in their groundstate and they will now be extended to the Po isotopes, where through alpha decay studies shape staggering was observed. Prior to the final experiment a new and efficient laser ionisation schemes for Po has to be studied (ISOLDE, K.U.Leuven). The detection system for this type of experiments is available.

*Coulomb excitation and transfer reactions using post-accelerated radioactive ion beams around Z=82.*

Once the HIE-ISOLDE project (upgrading the ISOLDE energy to 5 and later to 10 MeV/u and acceleration of heavier (A=200) isotopes) is operational, Coulomb excitation studies of the neutron-deficient Hg and Pb isotopes and transfer reactions will be executed within the proposed network. These experiments will probe the underlying components of the wave function and the outcome will be compared to and guide calculations beyond mean field and symmetry-based calculations (see below). A similar experimental set-up (MINIBALL germanium array surrounding a new reaction chamber equipped with highly segmented silicon detector) as for the investigations in the nickel region will be used.

In order to fully explore the post-accelerated ISOLDE beams a spectrometer is needed whereby the MINIBALL detector array can be used at the target or (in reduced form) at the focal plane position. This will allow the identification of reaction products and will increase the sensitivity of the

experiments substantially allowing studies with a much wider spectrum of energetic beams (see section 3).

**- Theoretical approaches**

*Shell-model and symmetry-based approaches*

At present, truncated shell-model studies treating up to 2p-2h,4p-4h excitations across the Z=82 shell within the Interacting Boson Model approach are carried out. In order to gain better understanding of the relation with mean-field studies, we (U.Gent – GANIL) shall study energy surfaces that can be derived using the coherent states corresponding to the IBM states. We aim at even going beyond the mid-shell region in order to explore the behavior of collective bands. This is an important topic to get a better understanding of mixing between the different bands. Present data on lifetimes in these nuclei (Köln) is bringing essential new input for understanding the global structures. We will also explore in greater detail E0 properties (radii, monopole transitions,..) in a consistent way. In order to also better understand where shell-model excitations are overtaken at lower energy by collective modes, we plan to carry out large-scale shell-model calculations using a closed proton core and the full open neutron space N=82 to N=126. For that purpose we shall have to construct a new optimized effective interaction.

*Beyond mean-field description of exotic nuclei*

The U.L.B. group has developed a method to include correlations beyond the mean-field by symmetry restoration and configuration mixing which has been shown to be well adapted to describe qualitatively the properties of nuclei in all regions of the mass table. Up to now, symmetry restrictions limit the applicability of the method to even-even nuclei with an axial quadrupole deformation.

The extension of this method requires the breaking of several symmetries, mainly axial symmetry and time reversal invariance. This development is underway since several years but is extremely delicate. Our aim during this program is to implement these extensions in several phases. First, a breaking of axial symmetry will improve the description of those even-even nuclei that are soft with respect to quadrupole deformations, in particular nuclei presenting shape coexistence. The breaking of time reversal invariance in even-even nuclei will allow to improve the description of spectra and is expected to correct the too low moment of inertia obtained up to now. The final step will be to extend the method to the description of quasi-particle excited states, which will enable to study nuclei with an odd number of neutrons or protons.

The description of nuclei along the N=20 isotonic line will constitute a major first test of these extensions. The very rapid variation of the properties of these nuclei has up to now escaped a coherent description by either the shell model or beyond mean-field methods, without an ad hoc renormalisation of single-particle levels. It is clear that the description of these isotones will require both to introduce several collective modes, like quadrupole deformations and rotation, and an improved energy density functional. They will thus constitute a very powerful test of all the developments that we plan to undertake.

**Objective 4:**

**We want to study medium-heavy and heavy closed shell nuclei in order to obtain key information to test and improve the predictive power of nuclear models far from stability**

| | **Workpackage 4:<br>Studies of medium-heavy and heavy closed shell nuclei** | **Partners** |
|---|---|---|
| 1 | Study of the changing shell structure in neutron rich nuclei near<br>N=20 and N=28 | K.U.Leuven – U.L.B. – U.Gent – GANIL - CSNSM |
| 2 | The influence of exotic neutron-to-proton ratios on the shell structure and the onset of collectivity in the neutron-rich Z=28 region. | K.U.Leuven – U.L.B. - U.Gent – CSNSM – Köln - GANIL |
| 3. | Intruder states in the Pb region and the microscopic origin of | K.U.Leuven – U.L.B. – U.Gent – |

| | | |
|---|---|---|
| | collectivity | GANIL – Köln – CSNSM - GSI |
| 4 | Proof the presence of spin-alignment in relativistic U-fission at the FRS-GSI. Investigate the changing shell structure near the doubly-magic neutron-rich $^{132}$Sn via moments measurements. | KU Leuven – Köln – GSI – CSNSM |

*<u>2.5 Nuclei along the N=Z line</u>*

Medium-mass nuclei near the N = Z line constitute an exciting field of study. Below 100Sn, valence protons and neutrons occupy the same single-particle orbitals and the large superposition of their wave functions reinforces the effects of the shell gaps. The shapes of these nuclei become extremely sensitive to the number of valence particles and small variations in these numbers may cause large differences in the resulting nuclear shapes. These equivalent high-spin proton and neutron orbitals give rise to exotic isomerism as well as rare decay modes (direct proton and two-proton decay) as recently evidenced for the decay of a 21+ isomer from 94Ag. The nuclei with equal number of protons and neutrons are also ideal laboratories to study the often subtle interplay between the T=1 and T=0 interactions. The underlying shell-model structure as well as the magnitude of the gaps on one side and the strength of the proton-neutron interaction especially in the T=0 channel on the other side can be studied by following the changing structure for N=Z nuclei starting from the p and sd-shell nuclei into the fp1g9/2 shell-model region. In order to study these phenomena, intense experimental and theoretical projects are proposed.

**Nuclear structure studies along the N=Z line**

*Mass measurements*

Mass measurements are particularly important along this set of nuclei as the results carry important information for testing the np – pairing and the Wigner term as well as for investigating collective behaviour that may be present for N=Z nuclei (e.g. near A=80 (Z=40,N=40) deformed intrinsic states show up). Extended experimental campaigns will be carried out at SHIPTRAP (GSI). The network will be involved in mass measurement of the neutron-deficient Mo through Ag isotopes (ground states and isomeric states). These data are of unique interest for the beta-decay studies planned at LISOL (see further beta-delayed proton decay along the N=Z nuclei) as well as for the mass determination of the recently discovered proton and two-proton decay state in $^{94m}$Ag. It will help e.g. to solve the problem of the anomalously high partial width for the two-proton decay in comparison to one proton disintegration observed for this (I=21$^+$) state in $^{94}$Ag. Also the exact excitation energy of isomers close to $^{100}$Sn will be crucial to disentangle the pn-interaction strength and the role of particle-hole excitations of the $^{100}$Sn core.

*Beta-decay studies at LISOL*

Using heavy ion fusion evaporation reactions in combination with the LISOL laser ion source, neutron-deficient Mo, Tc, Ru, Rh and Pd nuclei will be studied. These elements are difficult to study at conventional ISOL systems (not based on gas stopping) as they are refractory and thus difficult to extract from the target – ion source system. A newly developed decay spectroscopy station based on segmented germanium detectors and a planned efficient set of proton telescope detectors will deliver crucial information (half lives, level schemes, beta-delayed proton branching ratios) on these nuclei. This information, together with the mass measurements, will be compared with theoretical calculations (see below).

Another interesting possibility offered by medium-mass nuclei near the N = Z line is to study directly isospin symmetry probed by the weak and strong interaction. Isospin is strictly conserved by the strong interaction, but the Coulomb interaction mixes states with the same quantum numbers but different isospin. The isospin symmetry can be directly probed by comparing results from beta decay studies with their mirror charge exchange reactions. Recently, high resolution charge-exchange reactions on a number of nuclei have been determined at Osaka, Japan and the corresponding, short-lived beta-decaying isotopes will be studied at LISOL. A successful measurement on the decay

of 54Ni has been completed. Complementary information will be obtained using fragmented beams of 54Ni (GSI). For the other candidates (50Fe and 46Cr) laser ionisation schemes will be developed.

*Theoretical studies along the N=Z line*
Jointly with the theory group at GANIL, who has been exploring the interplay between T=1 and T=0 components using the symmetries of the interacting system, the U.Gent theoreticians intend to explore in particular the properties close to 100Sn. One of the issues is related to the Coulomb energy variation as a function of angular momentum and excitation energy, a topic that sheds light on modifications in the Coulomb energy with varying the overlapping proton-neutron orbitals. Another issue is related to the simultaneous treatment of T=0 and T=1 pairing correlations in mean-field methods. The U.L.B. group will develop its mean-field methods to include these correlations and will search for key data on which to adjust proton-neutron pairing.
A different approach starts from Monte-Carlo studies in which the full sd-fp region could be covered in order to determine the proton and neutron contributions separately. Contributions that manifest themselves in observables such as ground-state binding energy, summed electromagnetic strengths of electric and magnetic type, level densities (both intrinsic as well as J-distributions). These studies can now be performed as a function of the temperature of the interacting many-body system. The necessary methods and techniques have been developed to high precision during the last couple of years in the group at U.Gent and will be applied to the specific region. The experimental data obtained within the network (mass measurements, beta decay studies) will form stringent tests for these Monte-Carlo based model calculations.

**Weak interaction studies using nuclei along the N=Z line**
Because of the major efforts for a deep understanding of their structure, nuclei along and close to the N=Z line are very well suited for weak interaction studies. Different types of physics beyond the standard model can be probed by measuring correlations between the spins and momenta of either polarized or unpolarized nuclei. Examples of new physics phenomena, to which such experiments are sensitive, are e.g. exotic scalar or tensor components in the weak interaction, right-handed currents, and new sources of time reversal violation. For measurements which do not require polarized nuclei, often the superallowed $0^+ \rightarrow 0^+$ pure Fermi beta transitions are very well suited. For correlations requiring polarized nuclei the T=1/2 mirror nuclei or nuclei with pure Gamow–Teller transitions are good candidates, depending on the physics that is pursued. A recent review and overall analysis of presently available data yielded upper limits of about 8% (90%C.L.) for scalar as well as tensor coupling strengths relative to the known vector and axial-vector strengths.
In the past few years the K.U.Leuven team has developed two experimental set-ups to probe scalar and tensor weak currents in nuclear beta decay. The WITCH set-up was constructed and commissioned at ISOLDE-CERN and combines a double-Penning trap for sample preparation and purification with an electrostatic retardation spectrometer to measure the energy spectrum of recoil ions from beta decays in the second trap. The shape of this spectrum depends (via the beta-neutrino correlation) on the structure of the weak interaction and measurements with the mirror isotope $^{35}$Ar will provide new information on scalar currents. Tensor currents are being looked for with two low temperature nuclear orientation set-ups, one at Leuven and the other one (the NICOLE set-up) at ISOLDE. With these, precision measurements of the beta-asymmetry parameter for the pure Gamow-Teller decays of $^{60}$Co and $^{67}$Cu are carried out. Both high external magnetic fields (up to 13 T) and internal hyperfine magnetic fields are used. First results were recently obtained. The 2% absolute precision that was reached in a measurement with $^{114}$In demonstrates the feasibility of this type of measurement.
In the framework of the IAP project both methods will be further improved so as to reach the best possible precision and optimal sensitivity to non-standard model physics. For the WITCH experiment this will consist of installing more powerful (i.e. faster and position sensitive) beam monitoring devices, improving the injection efficiency into the 9 T magnetic field, optimising the procedures for trap operation, setting up a position sensitive MCP detector with large surface (i.e. 4 to 8 cm diameter) for the recoil ions, and the development of a dedicated beta detector for normalization purposes and for studying systematic effects. Finally, a design study for cooling (to 4 K) the ion

cloud in the Penning trap system will be performed. The aim is to reach a precision of 1% or better on the beta-neutrino correlation coefficient for $^{35}$A. This would permit to improve the present knowledge on scalar weak currents. These developments will be a combined effort of the Leuven team with the group of LPC-Caen that has recently set up a Paul trap for weak interaction physics at GANIL, GSI (SHIPTRAP) and ISOLDE (ISOLTRAP team).
The sensitivity and precision of the beta asymmetry parameter measurements will be increased by further improvements of the Monte Carlo simulation code, based on comparison with real data that will be obtained in realistic but widely varying experimental conditions, improvements in sample preparation to further reduce scattering in the sample foil and reach even larger nuclear polarizations (at present being about 65% for $^{60}$Co), and improvements to the detection electronics to obtain better long-term stability and lower noise conditions. The precision can then be increased to about 1% and possibly even better, which will be the best ever obtained for the beta asymmetry parameter of exotic nuclei. K.U.leuven and CSNSM will collaborate on this. The latter institute is preparing to install a low temperature nuclear orientation set-up at the ALTO facility at Orsay.

**Objective 5:**
**We want to study the nuclei along the N=Z line elucidating the neutron-proton pairing interaction, verifying isospin symmetry and studying the weak interaction in the atomic nucleus.**

| | **Workpackage 5:**<br>**Nuclei along the N=Z line** | **Partners** |
|---|---|---|
| 1 | Mass measurements of N=Z nuclei | K.U.Leuven - GSI |
| 2 | Theoretical studies along the N=Z line | U.Gent – U.L.B. - GANIL |
| 3 | Beta-decay studies along the N=Z line | K.U.Leuven – GSI |
| 4 | Improve the efficiency and sensitivity of the WITCH set-up | K.U.Leuven – GANIL - GSI |
| 5. | Optimise the determination of the beta-asymmetry parameter and obtain improved precision | K.U.Leuven – CSNSM |
| 6 | Weak interaction studies using the WITCH spectrometer and low-temperature nuclear orientation devices | K.U.Leuven – GANIL - CSNSM |

*2.6 Structure and reactivity of rare actinides*

The aim of this work package is to study the structure and reactivity of rare actinides in order to obtain a better understanding of the limit of nuclear stability for the heaviest nuclei and of the neutron-induced fission process on these exotic species, and to investigate the impact of these fundamental issues on accelerator driven systems like the proposed MYRRHA project at SCK•CEN. With the possible availability of an intense proton beam at the Mol site, we wish to explore the options to use this intense proton beam for specific nuclear-physics studies using intense Radioactive Source/Ion Beams from exotic nuclei in a decade from now.

The limit of nuclear stability for the heaviest nuclei is still unknown and is one of the most fascinating problems of nuclear physics. Due to the very small production cross sections, these nuclei are hard to reach experimentally. Their description by reliable models is also a difficult task, in view of the large number (around 300) of nucleons and the unusual neutron to proton ratios to which they correspond. A nice way to test models and to obtain constraints on single particle spectra for super-heavy nuclei is the study of the spectroscopic properties of transactinides. These nuclei are indeed deformed and the orbitals responsible for the quasi-particle excitations in these nuclei originate from the spherical orbitals populated. In collaboration with the experimental groups working in this area at the CSNSM, we plan to test the predictions of the mean-field models developed at the ULB concerning the presence of quasi-particle excitations in nuclei with Z=100 to 108. The existing data for Md (Z=101) and No (Z=102) indicate some deficiencies in the sequence of levels predicted by the actual effective interactions. We plan to test the improvements brought by newly introduced

terms in these interactions by studying the K-isomers in these nuclei. New data, on nuclei with Z=104 to 106 should become available during this program and will constitute severe tests of the interactions. These developments will permit to study K-isomers in other mass regions, in particular in the fission products of actinides. In addition, the current understanding of the astrophysical r-process indicates that the latter is terminated by spontaneous, β-delayed and neutron-induced fission. The (n,f) cross section data are therefore part of the input of r-process nucleosynthesis network calculations. Accurate σ(n,f) data are readily available for the common fissile isotopes, but this is less the case for the more exotic, rare actinides such as the Cm isotopes. Both the above mentioned theoretical and experimental efforts are needed to calculate the reactivity and transmutation properties of the future ADS system MYRRHA (SCK•CEN Mol).
Therefore the experimental groups from U.Gent and SCK•CEN plan to determine (n,f) cross sections on exotic rare actinides. The start of the project will be a measurement of the poorly known $^{245}$Cm(n,f) cross section as a function of the neutron energy as well as the (n,f) cross sections with thermal neutrons for a series of other Cm isotopes. Most Cm-isotopes are strong α-emitters, so strict precautions are needed for their manipulation. A dedicated experimental setup will be installed at a neutron beam of the GELINA facility in Geel to measure the $^{245}$Cm(n,f) cross section with resonance and high energy neutrons. In addition a new experimental setup for measuring thermal neutron-induced fission cross sections will be constructed at the BR1 reactor in Mol. The facility will be used to measure the $^{243}$Cm, $^{245}$Cm, $^{247}$Cm and $^{248}$Cm(n,f) cross sections. For the determination of the (small) $^{246}$Cm fission cross sections, a more intense neutron beam is needed which is available at the HFR of the ILL in Grenoble.

**Objective 6:**
**We want to study neutron-induced reactions on rare isotopes of interest for astrophysical and nuclear waste transmutation processes.**

| | **Workpackage 6:** <br> **Structure and reactivity of rare actinides** | **Partners** |
|---|---|---|
| 1 | Structure and reactivity of rare actinides, experimental determination of the Cm(n,f) cross section | SCK•CEN, U.Gent, U.L.B., CSNSM |

*2.7 Exploratory study for use of intense proton beams for fundamental nuclear physics studies*

The development of the accelerator driven system MYRRHA that serves as the basis for the European experimental XT-ADS is one of the important activities of SCK•CEN. The XT-ADS that is planned to be taken into service in Mol in 2016 will consist of a sub-critical nuclear core that is fed by neutrons produced in a heavy liquid metal (Pb-Bi eutectic) spallation target. A high power proton accelerator that is primarily used to irradiate the spallation target drives the whole system. At present two proton beam options will be investigated: 5 mA at 350 MeV or 2.5 mA at 600 MeV. The main goal of the XT-ADS is to provide protons and fast neutrons for experimental studies in the fields of materials research, nuclear transmutation studies and nuclear isotope production for medical applications. The purpose of this work package is to investigate the feasibility of extending the application field of the XT-ADS and its high power proton accelerator in particular to fundamental nuclear physics studies. In this way the use of the XT-ADS is optimised by broadening the scientific community that is served while in addition, the diminution of available experimental nuclear physics facilities in Belgium that is expected in the coming years can be countered.
In this workpackage several scenarios will be studied. These include sending a small portion (10-100 µA) of the high intensity proton beam to a dedicated irradiation station for nuclear physics applications. Alternatively, the use of the full beam during scheduled maintenance period of the XT-ADS spallation target and primary system will be looked into. The availability of these proton beams will be put in the broader scope of nuclear-physics research in Europe as outlined in NuPPEC's long range plan. Issues, complementary to the FAIR and EURISOL facilities, will be investigated following two main guidelines: availability of long beam time periods and of large primary proton beam intensities. This will lead us to investigate the interest and feasibility of ultra high-precision

experiments on exotic species. These experiments have often a rather low instrumental efficiency, require time consuming studies of systematic effects in the measurements and need long beam times. For example, using thermal diffusion from a high-temperature target and combining this with a simple single charge state ECR source followed by mass separation, intense sources of exotic nuclei from gaseous elements, like n-rich helium (6He, 8He), can be produced. The feasibility of laser spectroscopy measurements, decay studies, mass measurements, weak interaction studies and many other applications all with unprecedented precision will be investigated. The experience that exists in the network on radioactive ion beam research as well as with high intensity irradiation stations will be a key issue. K.U.Leuven, U.Gent, U.L.B., Köln and SCK•CEN will share the effort within this work-package. Here, the former partners will be mainly responsible for the nuclear-physics programme while the latter will study the technical feasibility of incorporating the irradiation station within the XT-ADS complex. The final outcome will be a report on the achievability of this study. Elements like technical feasibility, scientific importance, uniqueness and complementarity to other facilities in Europe around 2015 will be addressed in the report.

**Objective 7:**
**We want to investigate the feasibility of using the high power proton beam that will become available in the MYRRHA accelerator driven system for Belgian fundamental nuclear-physics research.**

| | **Workpackage 7:** **Physics with intense proton beams** | **Partners** |
|---|---|---|
| 1 | Feasibility/exploratory study of an irradiation station with 5/2.5 mA protons at 350/600 MeV, opportunities for Belgian fundamental research on radioactive nuclei on the long term | SCK•CEN, K.U.Leuven, U.Gent, U.L.B. - Köln |

<u>3. Development and/or upgrade of instrumentation</u>

The above-mentioned objectives can only be reached by upgrading the existing instrumentation and/or developing new instrumentation. Although these developments are an integral part of the different work-packages, we list below the major projects related to instrumentation.

*The MINIBALL array in combination with position sensitive silicon detectors*
In the previous phases of the network the MINIBALL detector set-up has been constructed and its first phase is now fully operational. It has been used at ISOLDE, the university of Köln and at GSI. Within a large international collaboration (including the MINIBALL collaboration), we plan to upgrade the detection system at ISOLDE that currently consists of the MINIBALL array in combination with a segmented silicon CD-type detector. For the transfer reaction studies a new reaction chamber including position sensitive silicon detectors covering almost $4\pi$ will be constructed. Also the electronics of the present CD detector has to be changed in order to reduce the dead time of the system. A solution will consist of multiplexing systems in combination with a digital read-out system. The latter is similar to the present MINIBALL digital electronics. This work will be done in close collaboration between K.U.Leuven en Köln.

*The detection system for beta-decay studies*
A new detection system using segmented germanium detectors in combination with plastic detectors has been constructed for beta decay studies at LISOL. This system will be upgraded with proton telescopes for the detection of beta-delayed proton emission. Both silicon and gas detector options will be investigated.

*A spectrometer for experiments at HIE-ISOLDE in combination with MINIBALL*
An international collaboration is being set-up to design and construct a spectrometer for radioactive beam experiments at the ISOLDE post-accelerator (REX-ISOLDE). With the planned energy upgrade of REX-ISOLDE to 5 and later 10 MeV/u and the availability of intense radioactive ion

beams a wide spectrum of experiments becomes possible. In order to identify the reaction products, a spectrometer should be installed. The MINIBALL array will be positioned at the target position. This will allow gamma, light-particle, recoil product correlation experiments, thereby boosting the sensitivity of the experiment. Different scenarios are currently under study taking into account the developments that are pursued at different places (EMMA - TRIUMF, the new spectrometer at JYFL, VAMOS – GANIL)

*The detection systems for WITCH and for the beta-asymmetry measurements*
To improve the precision attainable with the WITCH set-up and perform also spectroscopic studies with this system it will be upgraded with scintillator and semiconductor detectors for beta-particles, conversion electrons and low-energy gamma rays and X-rays.
For the beta-asymmetry measurements the detection electronics will be upgraded so as to obtain improved long-term stability and low noise conditions, which are essential to reduce systematic effects and obtain the high precision needed to investigate weak interaction properties.

*A set-up for measuring thermal neutron fission cross sections of exotic nuclei at the BR1 reactor in Mol.*
The network wishes to make use of the flexibility of the BR1 experimental graphite reactor in Mol for the determination of neutron induced fission cross sections of exotic very heavy nuclei. The set-up that will be constructed for this purpose at the BR1 reactor will include a vacuum chamber system, the detection system for neutron beam calibration and the fission product measurements, and the associated electronics and data acquisition system. The facility will be used to measure the $^{243}$Cm, $^{245}$Cm, $^{247}$Cm and $^{248}$Cm (n,f) cross sections.

4. The partners

The different research groups that make up this network possess truly complementary expertise. As successfully shown in the past and emphasized in the ex-post evaluation report as one of the strengths of the present IAP network, the combined theoretical and experimental research within the IAP network allows substantial progress on some pertinent questions at stake in nuclear-structure physics, astrophysics and fundamental interactions. The expertise from the Belgian groups spans a broad spectrum from theory (few-body models, mean-field descriptions and nuclear reactions at U.L.B., shell-model calculations and symmetries at U.Gent) to experiment (laser ionisation/spectroscopy, polarization and trapping of radioactive nuclei, moment measurements, decay- and reaction spectroscopy at K.U.Leuven, neutron reaction physics at U.Gent and SCK•CEN, high-intensity proton irradiated spallation targets at SCK•CEN). ISOLDE, GANIL and GSI are world-class radioactive ion beam facilities and possess a broad expertise in experimental as well as theoretical nuclear physics. The IKP (University of Köln) has expertise in highly segmented germanium detection systems, life-time measurements, theoretical and experimental nuclear-structure studies of medium- and heavy mass nuclei. At CSNSM (Orsay) theoretical (mean-field calculations) and experimental expertise (actinide spectroscopy, g-factor measurements, experimental nuclear astrophysics) are present.

Two new experimental groups joined the network: one from U.Gent with expertise on neutron-induced reaction physics and one from the SCK•CEN (“Belgian Nuclear Research Center”, ADS MYRHHA project). The neutron-reaction work is supported by the theory group from U.L.B., especially when related to astrophysics. The partners from the MYRHHA group lead the network to a natural extension towards fundamental aspects of the accelerator driven applications. The network embarks in an applied component and this makes the program truly interdisciplinary from nuclear-structure physics over fundamental interaction and nuclear astrophysics studies to nuclear physics applications. It should also be noted that, as mentioned before, the CRC Louvain-la-Neuve facility will continue to provide stable and radioactive ion beams at least for the first two years of the proposal period.

With respect to the EU partners, we have broadened the collaboration with two excellent research groups (CSNSM – Orsay –France and IKP – Köln - Germany) with whom the Belgian partners work on common research themes that are fully embedded in the proposed program. These groups have a broad spectrum of expertises that are to a large extent complementary. With the new network we wish to strengthen the collaboration with these new partners even more. As the collaboration with GANIL and GSI was very successful in the previous phase, they both stay as active EU partner in the network. It should be noted that most of the experimental campaigns will be performed at ISOLDE-CERN (Switzerland), GANIL (France) and GSI (Germany). The Louvain-la-Neuve radioactive beam facilities will be used in the first two years of the project. CERN, unfortunately, is not eligible to become a European partner in the network and therefore ISOLDE is not included.

Below we give a short description of the relevant research activities of the Belgian partners.

- “Instituut voor Kern- en Stralingsfysica”: Katholieke Universiteit Leuven (K.U. Leuven)

The nuclear physics teams of the IKS, KULeuven focus on two major topics in experimental nuclear physics research: the study of the structure of exotic nuclei and fundamental weak interaction studies.
Their research is performed with highly specialized experimental techniques and detection systems that are developed by the Leuven groups, mostly in international collaborations. The experimental set-ups are located at large-scale accelerator facilities, such as GANIL (Caen, France), GSI (Darmstadt, Germany), ISOLDE-CERN (Geneva, Switzerland), Jyvaskyla (Finland), the Paul Scherrer Institute (PSI-Villigen, Switzerland) and the CRC (Louvain-la-Neuve, Belgium). At the latter facility many of the specialized expertise of the Leuven teams has been developed before it was exported to the other facilities.
For the study of the structure of exotic nuclei, different experimental methods, like laser ionization, post acceleration and in-flight polarization of radioactive beams, have been developed and are being used by the Leuven groups. Amongst the experiments are spectroscopy measurements on very weakly-produced nuclei near the proton or neutron drip lines, measurements of nuclear ground state and isomeric state moments, measurements of the reaction properties of exotic radioactive beams interacting with stable nuclei, and measurements of the beta-decay properties of trapped ions and polarized nuclei for fundamental interaction studies. Each of these specialized methods helps to unravel the structure of exotic nuclei in a complementary way. Major efforts are being made to investigate the structure of nuclei near closed shells far from stability, near the N=Z line and in regions where new nuclear structure phenomena appear.
The weak interaction studies focus mainly on searches for interaction types in nuclear and neutron β-decay that are not included in the Standard Model, viz. right-handed currents, scalar and tensor interactions and time reversal violation. A dedicated set-up for measurements with unpolarized nuclei has been set up by the Leuven team at the on-line isotope separator ISOLDE at CERN, while measurements with polarized nuclei and neutrons are performed at ISOLDE, at the PSI and in Leuven.

- “Physique Nucléaire Théorique et Physique Mathématique” (PNTPM): Université Libre de Bruxelles (U.L.B.).

At the ULB, the nuclear physics program is mainly concentrating on theoretical and mathematical methods to explore and model the structure of the atomic nucleus as well as nuclear reactions, in particular to probe ‘exotic’ nuclei and nuclear reactions that are important to understand processes that govern element synthesis in stars.
There are a number of programs that essentially concentrate on a large spectrum of methods in order to explore nuclear physics at the lower energy side. Theoretical work aims to understand cluster structures and light halo nuclei using microscopic techniques such at GCM and R-matrix theory. On the other hand, there is a long-standing tradition to understand the appearance of mean fields inside nuclei starting from nucleon-nucleon effective forces. Reaction theory is another

important subject and is developed to describe heavy-ion scattering leading to a multitude of phenomena such as reactions that are of astrophysical interest or reactions probing light exotic nuclei at the drip lines . The reaction theory is needed to valorize the experimental reaction work, carried out with both stable as well as radioactive ions. On a deeper mathematical level, group theory and algebraic methods have been explored and developed and extended to super-symmetric quantum mechanics in order to understand observed phenomena in nuclei and nuclear processes on a very fundamental level.

- “Vakgroep Subatomaire en Stralingsfysica”: Universiteit Gent (U.Gent)

The nuclear physics teams of the “Vakgroep Subatomaire en Stralingsfysica” focus on both experimental and theoretical projects that cover nuclear structure physics and nuclear reaction studies related to nuclear astrophysics issues at the lower energy end. The theoretical research program also covers more general many-body systems.
The neutron-induced reaction work uses both low-energy neutrons at the ILL-reactor in Grenoble and combines it with higher-energy neutrons produced at the linear electron accelerator facility (GELINA) at Geel and is carried out within international collaborations. The theoretical program has three major subdivisions: (i) one part aims to understand the interplay between single-particle and collective motion using algebraic and shell-model methods and has strong links with many experimental groups world-wide studying shape coexistence and phase-transition phenomena, (ii) another part concentrates on correlations at the level of the nucleonic structure itself. Here, use is made of both electromagnetic as well as weak interaction probes to understand the hadron structure, covering an intermediate energy region, (iii) still another line of research explores the way in which the nucleus can be used as a ‘laboratory’ to study neutrino properties i.e. neutrino-nucleus interactions. On top of that, general many-body methods such as Monte-Carlo and statistical methods as well as exactly solvable methods are used to gain a better understanding of nuclei and their relation to other mesoscopic systems.

- Reactor Physics & MYRRHA : “Belgian Nuclear Research Centre” (SCK•CEN) Mol

The Belgian Nuclear Research Centre (SCK•CEN) was created in 1952, in order to give the Belgian academic and industrial world access to the worldwide development of nuclear energy with the early BR1 (1956) and later, the BR2 reactor (1961), which is still one of the most powerful research reactors in the world. The BR3 (1962), a prototype PWR reactor has been dismantled since and will be fully decommissioned in 2007. The major research projects at present, are related to reactor and fuel safety, radioactive waste handling, radiation protection and setting up of joint training programs with Belgian universities. The present nuclear installations/facilities are the BR1, BR2, and VENUS reactor, the HADES underground laboratory and the LHMA highly radioactive materials research lab. More recently the design and development of the MYRRHA ADS has been initiated. This installation will consist of a proton accelerator (350 or 600 MeV - 5 or 2.5 mA) delivering a proton beam to a liquid Pb-Bi spallation target, which in turn is coupled to a sub-critical fast core. It will serve as a basis for European experimental ADS activities and transmutation studies. The aim is to put it in use in 2016.

## I. 5. PARTICIPATION OF THE PARTNERS IN THE DIFFERENT WORKPACKAGES

Tick off in the table the participation of the different partners in the different workpackages (delete not used rows and columns in the table). Mention for each partner his/her name and the institution's abbreviation.

| | PARTNER | WP1 | WP2 | WP3 | WP4 | WP5 | WP6 | WP7 |
|---|---|---|---|---|---|---|---|---|
| P1 | Name : P. Van Duppen<br>Institution : K.U.Leuven | **O** | | **O** | **O** | **O** | | **O** |
| P2 | Name : P. Descouvemont<br>Institution : U.L.B. | | **O** | **O** | **O** | **O** | **O** | **O** |
| P3 | Name : K. Heyde<br>Institution : U.Gent | | **O** | | **O** | **O** | **O** | **O** |
| P4 | Name : H. Ait Abderrahim<br>Institution : SCK•CEN | | | | | | **O** | **O** |
| EU1 | Name : Ph. Chomaz<br>Institution : GANIL | | | **O** | **O** | **O** | | |
| EU2 | Name : Ch. Scheidenberger<br>Institution : GSI | **O** | | **O** | **O** | **O** | | |
| EU3 | Name : J. Jolie<br>Institution : IKP | | | | **O** | | | **O** |
| EU4 | Name : G. Chardin<br>Institution : CSNSM | | | | **O** | **O** | **O** | |

## I. 6. MAIN SKILLS OF THE PARTNERS

Describe the main skills of each of the partners in relation to the project (15 lines maximum per partner).
Delete not used lines.

P1 - Name : Piet Van Duppen
Institution : K.U.Leuven
Main Skills : experimental nuclear-structure research, weak interaction studies, production of exotic nuclei, laser ionisation, nuclear spectroscopy, segmented germanium detection systems, nuclear moments measurements, nuclear orientation techniques, nuclear reactions

P2 - Name : Pierre Descouvemont
Institution : U.L.B.
Main Skills : Cluster models, nuclear astrophysics, breakup reactions, nuclear structure and reactions, mean field theories, shell model, nucleus-nucleus interactions

P3 - Name : Kris Heyde
Institution : U.Gent
Main Skills : Nuclear structure: shell-model and collective models. General many-body techniques. Group-theoretical methods and dynamical symmetries. Experimental nuclear physics: neutron reactions and nuclear astrophysics. Radioactivity studies.

P4 - Name : Hamid Aït Abderrahim
Institution : SCK•CEN
Main Skills : 1. Design, execution and analyses of experiments in the fields of nuclear reactor physics, neutron dosimetry, gamma spectrometry, core physics and shielding. 2. Design and development of an accelerator driven subcritical system (ADS) including experiment design, target design, reactor core design, nuclear engineering, cost estimation and safety analyses

EU1 - Name : Philippe Chomaz
Institution : GANIL
Main Skills : production of exotic beams via intermediate energy fragmentation and with post-acceleration, nuclear theory, spectroscopy of and reactions with exotic nuclei

EU2 - Name : Christoph Scheidenberger
Institution : GSI
Main Skills : production of exotic beams via high-energy fragmentation, mass measurements, nuclear spectroscopy and reactions with exotic nuclei.

EU3 - Name : Jan Jolie
Institution : IKP - Köln
Main Skills : theoretical and experimental nuclear-structure physics: symmetry based models, in-beam spectroscopy, decay spectroscopy, segmented germanium detection systems, nuclear instrumentation electronics

EU4 - Name : Gabriel Chardin
Institution : CSNSM - Orsay
Main Skills : astroparticle physics

## I. 7. NETWORK ORGANISATION AND MANAGEMENT (4 pages maximum)

Describe the network's organisation and the practical terms governing collaboration and interaction between the partners (meetings, newsletters, doctoral school, ...).

The proposed network joins the Belgian efforts in the field of exotic nuclei research in a coherent way. It also encloses several younger Belgian research teams; for example, within the network 6 out of 15 permanent staff members that will work within the network are below 45 years of age.

We plan to continue the organisation and management aspects in the same manner as it was dealt with in the previous phase. The ex-post evaluation committee appreciated the way the network was organized.

*Steering committee*
The network management will be dealt with by the network committee composed of representatives from every partner and the coordinator. This committee will meet at least once a year and can be called in whenever necessary. The minutes of these meetings will be made available to the collaborators. At these meetings the scientific progress of the project, the practical organization of the network and financial matters will be discussed. The network committee will only perform eventual changes in the scientific program or in the spending profile of the budget after approval.

*IAP day*
An IAP day will be organized on an annual basis at the different institute of the Belgian partners. During this one-day workshop the PhD students and Post-Docs of the network present their work and ample time is given for discussion. After the talks, an open meeting on general aspects of the network will be held allowing the different collaborators of the network to express themselves and to plan future work.

*Workshops, seminars and symposia*
The different partners in the network will organize topical seminars given by invited specialists that are outside of the current network. Also national and international workshops in the spirit of the scientific program of the network will be organized by the partners of the network: a yearly meeting between nuclear physicists and astrophysicists will be organized at the U.L.B. – Brussels (sponsored by the “Groupe de Contact: Astrophysique Nucléaire”of the French Fund for Scientific Research FNRS), a yearly workshop on “Nuclear Physics under Extreme Conditions: Exotic Nuclei and Nuclear Astrophysics” will be organized in Leuven or Gent in the framework of a “Wetenschappelijke Onderzoeksgemeenschap” sponsored by the Flemish Fund for Scientific Research, and every two years a meeting sponsored by the Groupe de Contact : “Nuclear Physics in an European Context” of the French Fund for Scientific Research FNRS.

*Joint activities*
Joint experiments by the different experimental partners (K.U.Leuven, U.Gent, SCK•CEN, CSNSM, Köln, ISOLDE, GSI and GANIL) in the network will be performed on a very regular base. On these occasions, discussions with the international partners will take place as well.

*University courses and exchange of students*
Exchange of Ph.D. students and post-docs will be encouraged as it was done in the past. Furthermore, we will put special emphasis on the participation of the Ph.D. students in the Doctoral Schools at the other universities. In the framework of the new BaMa education system that is currently being installed at the Belgian universities joined courses are organized between the different universities. For example, K.U.Leuven master students will join courses on theoretical nuclear structure and astro-physics at U.L.B. Visa versa, experimental nuclear physics courses organized at K.U.Leuven are open for students from the other universities. This will allow to

exchange the expertise amongst the different partners on the level of the Master students and Ph.D. students. Occasionally, staff members of the network will give a series of lectures at other universities.

*Doctoral school*
The network is involved in the organization of international schools that cover the scientific theme of the networks proposal: Eurosummerschool on Exotic Nuclei (P. Van Duppen – K.U.Leuven is member of the board of directors), Ecole Internationale Joliot Curie (P.H.Heenen – U.L.B. is the Belgian representative in the international advisory committee), Fantom school (N. Severijns – K.U.Leuven is member of the Fantom Board). This will allow on the one hand spreading the expertise present in the network towards the international community of Ph.D. students and on the other hand to make sure that the Ph.D. students of the network are offered the opportunity to participate in lectures given by world experts.

*Web site*
A web site will be maintained where relevant information related to the network will be posted (internal reports, extracts from the minutes of the meetings, pre-prints, announcements of seminars). Furthermore, to respond to the ex-post evaluation, we will organize a competition for an IAP logo and acronym amongst the collaborators of the network. This logo will then be used to promote our network at international conferences and workshop in order to increase the visibility of our research activities.

## I. 8. RE-ORGANISATION OF THE PROJECT (maximum 3 pages)

*To be completed only if the initial proposal has to be adapted as a result of the selection outcome. If this implies changes in the composition of the network and/or the budget, it may be that it is not longer possible to pursue (achieve) the originally proposed objectives.*

In this case, describe and clarify the re-organisation of the project compared to the initial proposal.

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Due to budget restriction for the U.Gent partner the number of neutron capture cross sections measurement had to be reduced. This affects workpackage WP2 and WP6.

## I. 9. BUDGET (global distribution per partner for the 5 years)

(in EURO, without decimals)

The detailed distribution per partner is given in Section II

| | Name Partner | Institution | Budget |
|---|---|---|---|
| P1 | Piet Van Duppen | K.U.Leuven | 1.250.000 Euro |
| P2 | Pierre Descouvemont | U.L.B. | 400.000 Euro |
| P3 | Heyde Kris | U.Gent | 450.000 Euro |
| P4 | Hamid Ait Abderrahim | SCK•CEN | 400.000 Euro |
| EU1* | Philippe Chomaz | GANIL | 24.000 Euro |
| EU2* | Christoph Scheidenberger | GSI | 24.000 Euro |
| EU3* | Jan Jolie | IKP - Köln | 26.000 Euro |
| EU4* | Gabriel Chardin | CSNSM - Orsay | 26.000 Euro |
| **TOTAL BUDGET** | | | 2.600.000 Euro |

* The budget for the EU-partner is the budget attributed by the IAP-programme only (without the 50% contribution of the EU-partner)

* The budget for the EU-partner is the budget attributed by the IAP-programme only (without the 50% contribution of the EU-partner and with a maximum of 150.000 EUR per proposal).

## I. 10. PREVIOUS IAP-PHASES

*To be completed only if the present network was funded during earlier phases of the IAP programme.*

Mention the earlier phases of the IAP programme (I, II, III, IV, or V) and the titles of projects in which the partners of the present network has participated.

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**Phase I (1987-1991):** The production and acceleration of radioactive ion beams and their use in nuclear physics, nuclear astrophysics and solid state studies (U.C.L., U.L.B. and K.U.Leuven)
The study of the excitation and ionization of multiply charged ions by electrons and photons (U.C.L.)
**Phase II:** Radioactive ion beams (addition to phase I)
**Phase III (1992-1996):** Radioactive ion beams (U.C.L., U.L.B. and K.U.Leuven)
**Phase IV (1997-2001):** Production and use of radioactive nuclear beams in nuclear astrophysics and nuclear physics (U.C.L., U.L.B. and K.U.Leuven)
**Phase IV (2002-2006):** Exotic nuclei for nuclear physics and nuclear astrophysics (U.C.L., U.L.B., K.U.Leuven and U.Gent; EU: GSI and GANIL)